MICROWAVE CHARACTERISTICS OF BULK HIGH-Tc SUPERCONDUCTORS

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ABSTRACT

Currently most available high-T_c bulk material is in disk form that does not lend itself readily to microwave loss measurements. This paper describes a resonant measurement technique using low impedance disk resonators. The configuration enhances the influence of conductor losses on the resonator Q and thereby permits the evaluation of disks as a function of temperature in a relatively simple test configuration with good accuracy. Measurements on bulk $Y\,Ba_2\,Cu_3\,0_{6+x}$ material will be described with conductivities at X-band ranging up to 10 times that of Au at 65°K.

INTRODUCTION

Superconductivity is not new to the microwave area. A number of papers [1-3] have dealt with various studies and applications of low-T_c superconductive materials over the past two decades. Aside from some very specialized cases, however, widespread use of superconductors so far has not been deemed cost effective because of the very low temperatures that would have to be maintained for superior microwave performance.

The discovery of high-T_c materials and the flury of activities at numerous universities and laboratories all pursuing higher and higher transition temperatures, conductivities and current densities has changed this situation dramatically. If, for example, materials with conductivities 3 orders of magnitude higher than copper operating at liquid nitrogen temperatures or above could be realized, a variety of passive microwave components such as, filters, multiplexers, and delay lines could be developed in sizes compatible with MIMIC technology. In addition, other components such as high stability oscillators could be made to have greatly improved performance if ultra high-Q cavities were available. The above examples touch upon advantages to be derived from superconductors applied to passive microwave components. Obviously, from a long range point of view, improved active devices might have an even more dramatic impact.

At present, the main interest centers on the question of what characteristics do these new materials have at microwave frequencies. Does floating a magnet mean good microwave properties? Necessary, but certainly not sufficient! Since most of the readily available materials from various sources presently come in disk form, this paper presents a measurement technique especially suited for samples of this type. After describing the advantages and peculiarities of this measurement technique, results for the best material tested so far are presented.

DISK RESONATOR MEASUREMENT TECHNIQUE

Previously reported measurements on superconducting disks either insert the disk (or chips of material) in a high-Q cavity, or use the disk as one of the cavity walls [4,5]. The main difficulty with such arrangements is that the superconducting material represents only a small portion of the resonator. Improvements in Q of such composite resonators at the transition temperature indicate that a superconducting effect takes place, but meaningful quantitative information is difficult to obtain and is generally masked by uncertainties in the Q measurement. The most effective method would be to make the entire resonator out of superconductive material by fabricating, for example, a TM_{011} resonator out of two cup-shaped parts. The need for relatively large cylinders of material and the associated machining or shaping does not make this technique very attractive.

The measurement set up described in the following uses regular disks to form a low impedance disk resonator for measuring the resistivity of the superconducting material as a function of temperature. Figure 1 shows the basic arrangement. A small disk (typically 1/2" diameter) is placed on top of a larger disk with a dielectric spacer (typically 2 mil or smaller) between the disks. The resonator is excited by a coaxial probe that penetrates the large disk in close proximity of the smaller disk. A resonator of this type has a quality factor Q_t given by

$$\frac{1}{Q_t} = \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_r}$$

where Q_c is dependent on the conductor losses, Q_d on the dielectric losses and Q_r on radiation losses.

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In order to get good quantitative information on the conductor losses, it is important to shape the resonator in such a way that the conductor losses become dominant compared to dielectric and radiation losses. Simplified expressions for the three Q values of a disk resonator are given below [6].

$$Q_c = h\sqrt{\pi f \mu \sigma} \quad (1)$$

where h is the spacer height, f is the resonant frequency, μ is the conductor permeability and σ its conductivity.

$$Q_d = 1/\tan\delta \quad (2)$$

where tan δ is the loss tangent of the dielectric spacer.

$$Q_r = 240 \{(ka)^2 - n^2\}/(h\mu f(k_o a)^2 I_1), \quad (3)$$

where ka = 1.84 for the dominant mode (n=1), and

$$I_1 = \int_0^{\pi}[\{J_{n+1}(k_o a \sin\theta) - J_{n-1}(k_o a \sin\theta)\}^2 + \cos^2\theta \{J_{n+1}(k_o a \sin\theta) + J_{n+1}(k_o a \sin\theta)\}^2] \sin\theta \, d\theta$$

J_n (x) are Bessel functions of order n and argument x, $k_o = 2\pi/\lambda$, and a is the disk radius.

For a given material, it becomes apparent that reducing the thickness of the dielectric spacer has no effect on the dielectric Q but increases the radiation Q and decreases the conductor Q. Thus a resonator made with a very thin dielectric material will be dominated by conductor losses and improvements due to superconductivity effects will be readily and accurately represented. From a practical standpoint, we started with a disk resonator geometry that still provides readily measurable Q values for metallic disks (in the order of 10 to 50), and keeps other losses as low as possible ($Q_d > 2500$; $Q_r > 400$). Also the top disk has two small parallel flats ground onto the outer diameter to split doublet modes and prevent broadening of the Q-curve*. The theoretical expressions listed for the Q values before are only approximate since they do not take into account the thickness of the top disk and the fringing fields due to the sidewalls of the disk. Nevertheless, accurate resistivity measurements can be obtained by comparing measured Q-values from superconducting disks with those of regular metal disks.

EXPERIMENTAL RESULTS

The measurements were carried out in a 3 inch ID Cryostat, shown in Fig. 2, that permits cooling to liquid helium temperatures in a single evacuated envelope. An HP8510B network analyzer was used for the characterization of the single-port resonator structure at different temperatures. The resonator response was deembedded for this purpose from the internal connection and the RF feed by a computer controlled calibration procedure. Both phase and amplitude of the reflection coefficient were used for the determination of the Q-factor.

The measurement set up was first calibrated with a series of measurements on Au plated brass disks with different dielectric spacer thicknesses. Table 1 shows the results of Q_t for metal disks with a polyethylene spacer ranging from 1.2 to 6 mil. Also listed are theoretical values for Q_c, Q_d and Q_r. Overall, the resonator structure behaves reasonably well compared to theoretical expectations and thus forms a good comparison basis for the subsequent measurements with superconducting disks.

TABLE 1. Q-Values for Metal Disk Resonator at Room Temperature

	Measured		Theoretical (No cover)			
Thickness (mil)	Q_t (no cover)	Q_t (with cover)	Q_c	Q_d	Q_r	Q_t
1.2	34	37	30.5	2500	645	29
2	42	49.2	50	2500	389	44
6	70	149	151	2500	133	69

where $\sigma = 2.5\times10^7$ mho/m, $\varepsilon_r = 2.1$, tan $\delta = 0.0004$ at room temperature.

Au plated disk resonator structures with 1.2 and 2 mil polyethylene spacers were then calibrated as a function of temperature. The measured Q-values converted to bulk resistivity are plotted in Fig. 3. The values obtained are somewhat higher than the theoretical values for gold which is as expected, since no special attention was given to surface preparation or plating optimization. The resonance frequency is also somewhat lower than that of a thin film disk resonator for which theoretical values are readily available. The discrepancy is due to the fringing field loading from the thickness of the disk. Mode splitting (typically ~200 MHz) was observed in agreement with using disks that have two parallel flats ground on the perimeter.

A number of superconducting disks using material from various sources were measured to investigate the conductivity improvement due to the superconductive effect at different temperatures. Unfortunately, most materials even though they may show a Meisner effect and have some claims of "zero" DC resistance associated with them, did not produce measurable Q's at or near their transition temperature. The best results were obtained on an experimental

*In a system with perfect rotational symmetry two modes can be excited, one with zero and one with maximum field at the excitation point. Slight asymmetries can then lead to the excitation of both modes with a resulting broadening of the Q-curve.

material obtained from Rutgers*. This material consisting of a Y $Ba_2Cu_3O_{6+x}$ composition showed bulk resistivity values equal to that of plated Au at the transition temperature and improved drastically at still lower temperatures as shown in Fig. 4. For the run using a 2 mil polyethylene spacer a Q of 480 was observed at 35°K. Since the Q remained practically constant from there towards lower temperatures, radiation losses may be a limiting factor. Further measurements using a 1.2 mil spacer (see Fig. 5) showed the expected decrease in starting Q due to the lower characteristic impedance of the resonator. It also showed a slightly higher end-Q at 10°K. Converting this value to bulk resistivity indicates that the material is approximately 100 times better than plated Au at 10°K.

CONCLUSIONS

The results obtained so far show these materials are not yet really useful for microwave applications. They do show, however, that even the current bulk material (rather coarse and porous by microwave standards) can reach bulk resistivity values two orders of magnitude lower than that of a good metal conductor, albeit at temperatures well below the DC transition point. With rapid advances taking place in the processing area especially in thin films, there are strong expectations that a superior superconducting material suitable for microwave frequencies will become available soon.

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*Courtesy Prof. A. Safari, Rutgers University, Piscataway, N.J.

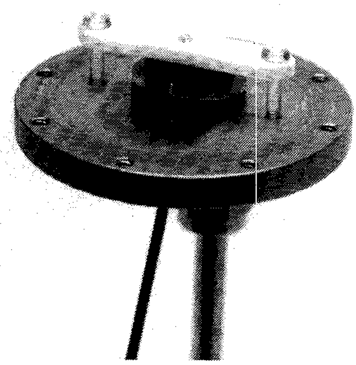

Figure 1. Disk resonator with probe coupling.

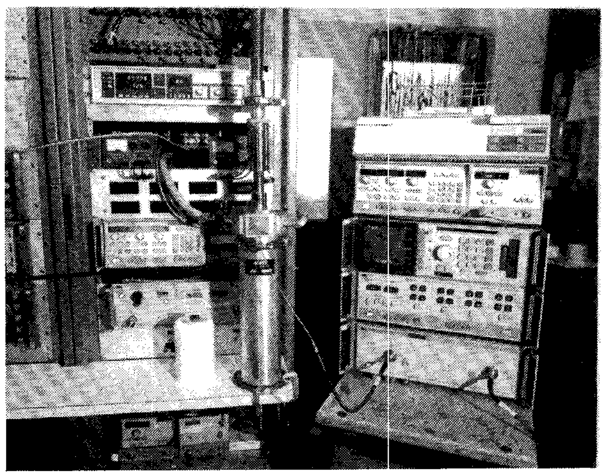

Figure 2. Cryostat and microwave test station.

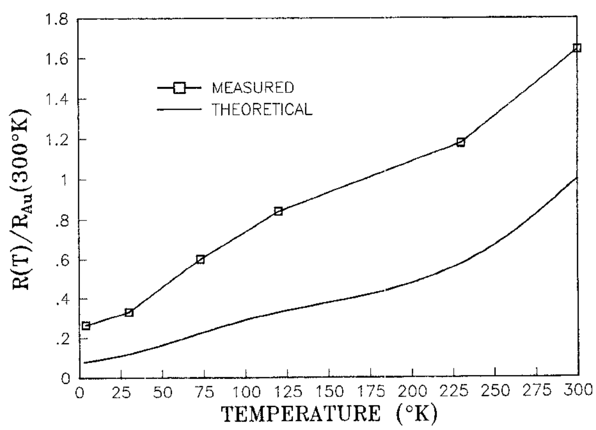

Figure 3. Normalized bulk resistivity as a function of temperature.

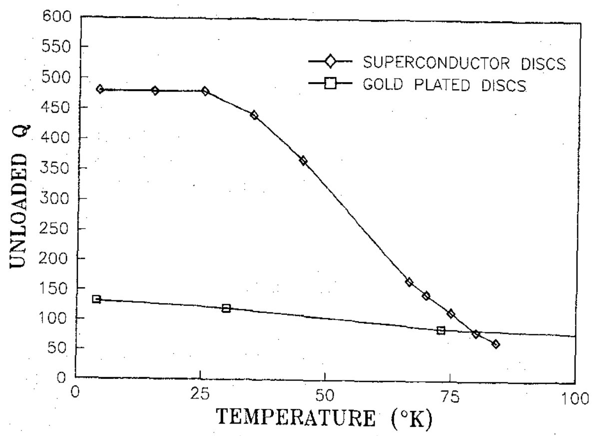

Figure 4. Q-values of disc resonator with 2 mil dielectric spacer.

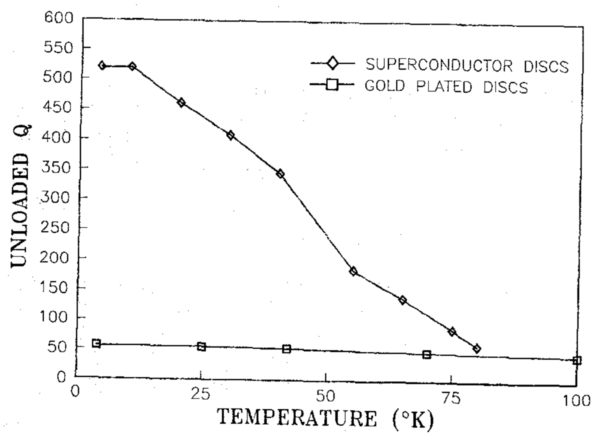

Figure 5. Q-values of disc resonator with 1.2 mil dielectric spacer.